A Simplified Approach to the Physics of Runaway Electron Beam Dissipation in Tokamak Disruptions

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1. Introduction   The injection of large amounts of high-Z impurities by Massive Gas Injection (MGI) or Shattered Pellet Injection (SPI) constitutes the most promising candidate for the mitigation of runaway electrons (RE) during disruptions in large devices like ITER [1,2]. In this paper, the dissipation and decay of the RE current by injection of high-Z impurities during tokamak disruptions is analyzed using a simplified approach, based on the kinetic treatment of Ref. [3], which includes the effect of the collisions with the plasma particles and the impurity ions, the synchrotron radiation losses associated with the pitch angle scattering of the REs when colliding with the impurity atoms as well as the bremsstrahlung radiation. The model allows to get simple estimates of the RE current duration, the RE distribution function and energy during the dissipation phase. A comparison of the effects associated with the different runaway loss mechanisms (collisions, synchrotron and bremsstrahlung radiation) will be also presented.

2. Basic equations   The starting point is the assumption that the dissipation of the runaway current is determined by the time at which the accelerating electric field drops below the threshold electric field (E_R) for RE generation. Hence, if $G_0(q)$ is the initial ($t = 0$) runaway momentum distribution function ($q \equiv p/m_e c$), the runaway density at time t and its decay rate can be written:

$$n_r(t) = \int_{q_0}^{q_0^{max}} G_0(q)\, dq \Longrightarrow \frac{dn_r}{dt} = -\frac{dq_0}{dt}\, G_0(q_0), \tag{1}$$

where q_0^{max} is the maximum runaway momentum at the start of the decay ($t = 0$) and q_0 is the electron momentum dropping to zero after time t, determined by the RE energy dynamics, $dq/dt = U(q, t)$. The resulting distribution function at t is given by

$$G(q, t) = G_0\left(q_0(q, t)\right)\, \frac{dq_0}{dq}. \tag{2}$$

Here, $q_0(q, t)$ indicates the initial electron momentum (at time $t = 0$) dropping to q at time t, $q_0(q, t) = q - \int_0^t U(q', t')\, dt'$, and dq_0/dq represents the effect of the changes in the electron momentum interval, dq, during the dissipation of the electron energy. Finally, the electron flow velocity in momentum space, U(q), describing the RE dynamics can be approximated by [3]:

$$\frac{dq}{d\tau} = U(q) = \left(\frac{1}{\tanh A} - \frac{1}{A}\right) D - \left(1 + \frac{1}{q^2}\right) - F_{gy} \frac{Z+1}{D} \frac{1+q^2}{q} \left(\frac{1}{\tanh A} - \frac{1}{A}\right)$$
$$-(1 + Z)\, F_{br}\, (1 + q^2)^{1/2}, \tag{3}$$

where $D \equiv E_{||}/E_R^{coll}$ ($E_R^{coll} \equiv e^3 n_e \text{ln}\Lambda/4\pi\varepsilon_0^2 m_e c^2$ is the critical field due to collisions), $\tau \equiv \nu_r t$ is the time normalized to the electron collision time ($\nu_r = n_e e^4 \text{ln}\Lambda/4\pi\varepsilon_0^2 m_e^2 c^3$), $F_{gy} = 2\varepsilon_0 B_0^2/(3 m_e \, n_e \, \text{ln}\Lambda)$ characterizes the strength of the synchrotron radiation effect, $A = [2D/(Z+1)] \cdot q^2/\sqrt{1+q^2}$, and $F_{br} \equiv (1/137\,\pi) \cdot (\text{ln}\Lambda_B/\text{ln}\Lambda)$ with $\text{ln}\Lambda_B = \ln 2\gamma - 1/3$ (γ is the electron relativistic gamma factor).

Eq. (3) includes the effect of the accelerating electric field (first term), the collisions (second term), as well as the synchrotron radiation (third term) and bremsstrahlung losses (fourth term).

3. Runaway beam mitigation in ITER   Here, using the formalism described above, we investigate the mitigation of a plateau RE current in ITER when the formation of the RE beam cannot be avoided during the current quench (CQ) phase of the disruption. Ar injection will be considered, more efficient in this phase than the injection of Ne due to its larger atomic number. The simulation is carried out using a simple zero dimensional model, including the replacement of the plasma current by the RE current, $E_{||} = \eta \, (j_p - j_r)$ [$j_{p,r} = I_{p,r}/\pi a^2 \kappa$ are the average plasma and runaway current densities, respectively, a the plasma minor radius and κ the plasma elongation]. The total current I_p is calculated according to $dI_p/dt = -(2\pi R_0/L) \cdot E_{||}$ ($R_0 \sim 6.2\,\text{m}$ is the major radius and $L \sim 5\,\mu\text{H}$ the internal plasma inductance), and the RE current decay is obtained using Eq. (1). In the simulations, the effect of the collisions with the free and bound electrons of the impurities will be included and, at the start of the dissipation phase ($t = 0$), an avalanche-like shape distribution, $G_0 \propto \exp(-q/\overline{q}_0)$, will be assumed. An example is illustrated in Fig. 1, corresponding to the mitigation of a plateau RE current of 10 MA / 20 MJ (average electron energy $\sim 15\,\text{MeV}$) in ITER (assuming $\tau_{res} \sim 30\,\text{ms}$) for different amounts of assimilated Ar. The left and right figures show, respectively, the evolution of the RE current and the electric field during the dissipation phase. The sudden increase of the critical field for RE generation (E_R) due to impurity injection leads to the drop of the RE current (I_r) which results in an induced electric field which, if the amount of impurities is low enough (1 and $2\,\text{kPa} \cdot \text{m}^3$ in the figure), raises and remains close to the critical electric field during the decay (marginal stability scenario [3]) and, hence, the ohmic current keeps closely constant resulting in a linear decay of I_p and I_r. When the amount of impurities injected increases, the plasma and RE current evolution during the decay gradually departs from the marginal stability condition, and $E_{||}$ falls well below E_R for the largest amount of impurities ($5\,\text{kPa} \cdot \text{m}^3$ in the figure).

Left Fig. 2 shows the runaway distribution function, $G(q,t)$, calculated from (2), at different times during the dissipation phase for an amount of $2\,\text{kPa} \cdot \text{m}^3$ of assimilated Ar and assuming collisional losses alone. The red line indicates the initial avalanche-like distribution. It is observed that the high energy tail keeps the initial exponential shape during the current decay. The effect of the collisions increases at lower q yielding the observed depletion of $G(q)$. The addition of both, synchrotron and bremsstrahlung radiation losses (illustrated in right Fig. 2), enhances the energy dissipation at high energy which leads to a steepening of the distribution in the high-q region which increases with time. Indeed, solving the momentum equation (3) in the limit of high-q it can be shown that $G(q,t) \propto \exp\left(-\frac{q}{\overline{q}(t)}\right)$ with $\overline{q}(t) \equiv \overline{q}_0 \exp\left(-\int_0^\tau (1+Z)\left(\frac{F_{gy}}{D} + F_{br}\right) d\tau'\right)$,
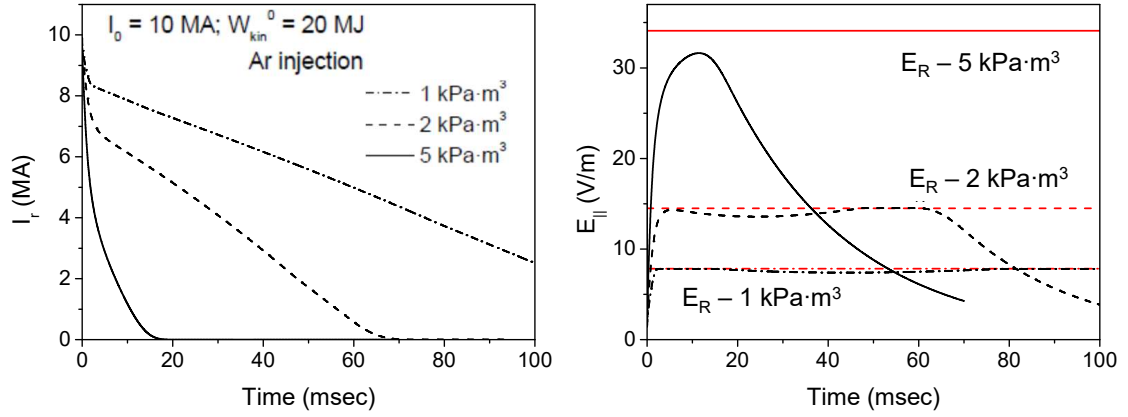
Figure 1: For the mitigation a 10 MA / 20 MJ plateau RE current in ITER ($L = 5\,\mu\text{H}$; $\tau_{res} \approx 30\,\text{ms}$): Time evolution of the RE current (left) and electric field (right) for different amounts of Ar (1, 2 and 5 $\text{kPa} \cdot \text{m}^3$) including the effect of the collisions, synchrotron and bremsstrahlung radiation losses. The values of E_R for each amount of assimilated Ar (horizontal red lines in right figure) are shown for comparison.

where $\tau \equiv \nu_r t$), indicating the increase of the steepening in the high energy region during the dissipation phase. At the same time, the collisions deplete the distribution at low energies whereas an accumulation of electrons and a transient increase of $G(q)$ occurs for intermediate q values until, at sufficiently long times, the whole distribution decays. The combination of the steepening at high q together with the depletion at low energy leads to the characteristic bump formation. On the other hand, the radiation losses, enhancing the energy dissipation at high energy, increase the decay rate of the RE kinetic energy (W_{kin}) in comparison with the decay of the RE current.
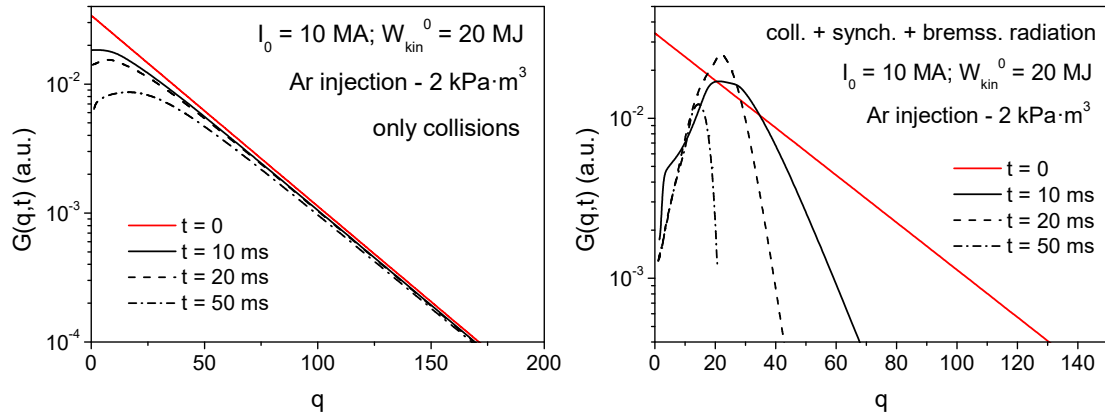

Figure 2: Calculated runaway distribution, $G(q,t)$, at different times during the mitigation a 10 MA / 20 MJ plateau runaway current in ITER by injection of $2\,\text{kPa} \cdot \text{m}^3$ of Ar assuming collisional losses alone (left) and including the effect of the synchrotron and bremsstrahlung radiation (right). The red line corresponds to the initial avalanche-like distribution.

A crucial issue for ITER is to assess if the injection of a sufficiently amount of impurities onto a plateau RE beam when its formation cannot be avoided during the CQ

phase of the disruption, might provide an efficient defense mitigating the RE beam before significant energy is deposited on the first wall or divertor components. Fig. 3 shows the estimated dissipation time of a plateau RE beam of 10 MA / 20 MJ in ITER-like conditions as a function of the amount of assimilated Ar in the plasma assuming collisions alone and adding the effect of the synchrotron and bremsstrahlung radiation. These results, taking into account that the characteristic time in ITER for the vertical instability growth is ~ 100 ms, suggest that injection of a few $\text{kPa} \cdot \text{m}^3$ of Ar ($\geq 2\,\text{kPa} \cdot \text{m}^3$) could be a promising scenario for RE electron dissipation during disruptions. Nevertheless, a uniform distribution of the impurities in the plasma has been assumed but the assimilation of the injected particles has to be further assessed, since experiments on impurity injection point out to low efficiency and poor penetration into the plasma. Moreover, DINA simulations have shown that the required impurity quantities for RE beam dissipation can be higher if the plasma dynamics during the CQ is taken into account as it has been found that rising the impurity density accelerates the VDE of the plasma so that the termination of the RE current can be initiated earlier than the beam has been dissipated, increasing the electric field and the amount of energy deposited onto the REs.
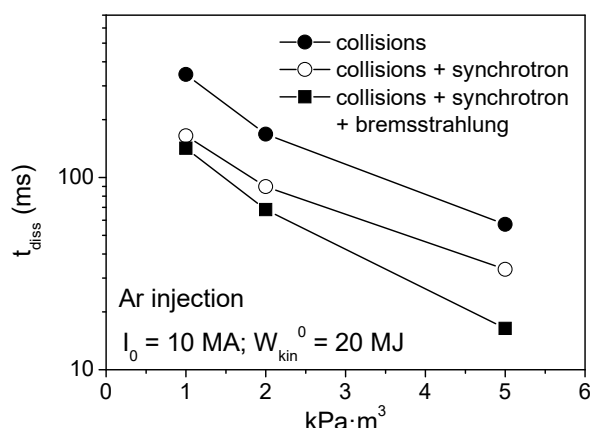

Figure 3: Calculated dissipation time for the mitigation of a plateau RE beam of 10 MA / 20 MJ in ITER-like conditions as a function of the amount of Ar assimilated in the plasma assuming collisions alone (full dots) and including the effect of the synchrotron (open dots) and bremsstrahlung radiation (black squares).

References
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